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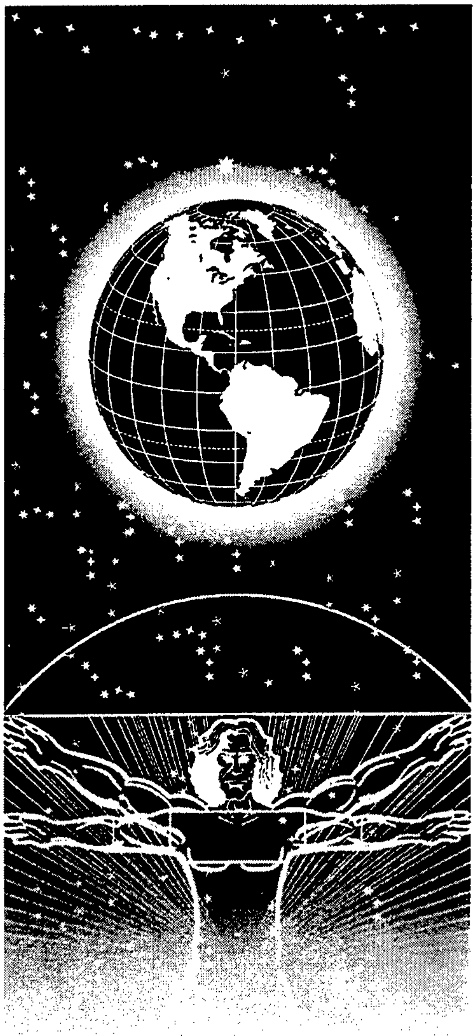

UNITED STATES AIR FORCE RESEARCH LABORATORY

EXAMINING THE RELATIONSHIP BETWEEN MENTAL WORKLOAD AND SITUATION AWARENESS IN A SIMULATED AIR COMBAT TASK

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13. ABSTRACT *(Maximum 200 words)*

Seven pilots participated in an experiment designed to assess the relationship between mental workload and situation awareness. Participants flew simulated air intercepts against four bombers supported by two fighters. The experiment contrasted two cockpit designs. The conventional cockpit used traditional independent gauges for flight and tactical information. The virtually augmented candidate cockpit used advanced interface concepts. The task scenario consisted of four mission phases that were designed to influence pilot mental workload and situation awareness. An inverse relationship was observed between mental workload and situation awareness as influenced by cockpit design and phase of mission. This shows the importance of assessing both mental workload and situation awareness when assessing system effectiveness.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

During the preparation of this report, Amy Alexander was a member of the Senior Honors Thesis program at the Ohio State University.

The analyses and writing of this technical report were conducted as part of the Air Force Research Laboratory, Human Effectiveness Directorate, Student Practicum Program. Ms. Alexander participated in the Student Practicum program from January through June 2000.

The data collection for this research was collected as part of the Vista Warrior project. Vista Warrior was one component of Project Arrangement US-UK-AF-95-0006 under the US-UK Technology Research and Development Projects (TRDP) Agreement signed on 19 July 1996, which called for a four-year cooperative effort.

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INTRODUCTION

When evaluating cockpit systems, the question often arises as to how the goodness of an interface or concept design is assessed. A paradigm using design driver measures, such as mental workload and situation awareness, has been suggested as an alternative to past techniques which have been shown to be quite limited (Selcon, Hardiman, Croft, & Endsley, 1996). Design drivers have been defined as models of performance that serve as guidelines for designing displays. Specifically, all other things being equal, less mental workload is better just as more situation awareness is better. It is possible that mental workload may be too low leading to boredom and eventual errors (Tsang & Wilson, 1997), but this is not expected to occur in air combat missions and is therefore not within the scope of this study. In terms of mission effectiveness and safety, a system that exerts both moderate mental workload and high situation awareness will be best under demanding or unexpected conditions. This paper will look at mental workload and situation awareness as separate constructs, and then discuss the relationship between them.

Although there is debate over the definition of "mental workload," it is commonly referred to as "that portion of the operator's limited capacity actually required to perform a particular task" (O'Donnell & Eggemeier, 1986). Previous research has shown that performance drops in accordance with unfavorably high or low levels of mental workload (Tsang & Wilson, 1997). Specifically, system failure and errors may occur when mental workload is too high. Since skilled operators often employ compensatory efforts to disguise excessive demands, it has become important to assess mental workload so that systems can be designed to prevent unfavorable levels of mental workload from occurring. Assessment of mental workload has included performance-based, physiological, and subjective measurements. Based on the assumption that the operator is aware of excessive levels of mental workload, the most common form of assessment has revolved around subjective measures (Tsang & Wilson, 1997).

Although mental workload has been demonstrated to be important in assessing systems, it does not tell anything about the quality of the information the operator is using. To address this need, the concept of situation awareness and its measurement have emerged. Situation awareness is the "continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing future perception and anticipating future events" (Dominguez, 1994). This definition identifies three specific levels of situation awareness: 1) perception of elements in the environment; 2) comprehension of the current situation; and 3) the projection of future status. In other words, it is the central organizing knowledge from which all decision making and action takes place. Previous research has shown that increased levels of situation awareness allow pilots to function in a timely and effective manner (Endsley, 1993). Common ways of measuring situation awareness include memory probe techniques, operator reactions to critical stimuli, and subjective ratings (Vidulich, Dominguez, Vogel, & McMillan 1994).

It has been questioned if a relationship exists between mental workload and situation awareness. Endsley (1993) suggested that "situation awareness and [mental] workload, although inter-related, are hypothesized to be essentially independent constructs." Her research emphasized the independence by showing that mental workload ratings and memory probe measures of situation awareness in an air combat task were uncorrelated. Fracker and Davis (1991) also found a disassociation between mental workload and situation awareness. Their research showed that situation awareness ratings remained constant while mental workload ratings increased with task difficulty.

In contrast to the findings suggesting independence, it is routine for designers of new systems to propose that the new system will both decrease mental workload and increase situation awareness (Vidulich et al., 1994). In fact, Vidulich (in press, b) has found that such a pattern tends to occur if the new system is improved by reformatting the data that were previously available in the old system. Furthermore, it is possible that in some situations the attainment or maintenance of high situation awareness could demand higher mental workload (Tsang & Wilson, 1997). Since both mental workload and situation awareness are important design drivers, it is necessary to resolve whether there is a relationship between these measures or if they are typically independent.

The present experiment examined the relationship between mental workload and situation awareness as both were influenced by changes in the interface design and task demands. The interface modification involved the reformatting of currently available data through a virtually-augmented display. Extrapolating from Vidulich (in press, a), it was predicted that the new display would show lower mental workload and higher situation awareness than the conventional cockpit. Task demands changed across different phases of the flight as more complex situations were encountered that followed more complex rules of engagement (ROE). As the task phase became more complex, it was expected to inflict higher mental workload associated with lower situation awareness. In this experiment, mental workload was measured using subjective ratings. Situation awareness was assessed by the operator's compliance with the complex ROE. More explicitly, these expectations have led to the following hypotheses:

1. Comparisons of ANOVA results will show that the cockpit inflicting higher mental workload will be associated with lower measures of situation awareness. The phases of flight inflicting higher mental workload will also be associated with lower measures of situation awareness.

2. Mental workload ratings across cockpits and phases of flight will be negatively correlated with situation awareness scores.

METHOD

Participants

Seven current or previous male United States military pilots with a mean age of 45.28 years (SD = 8.15 years, range = 33 - 56 years) participated in this study. Overall flight hours ranged from 1100 to 8830 with a mean of 3411.02 hours (SD = 2531.23). Six pilots had fighter aircraft experience including A-7, A-10, F-4, F-5, F-14, F-15, F-16, F-17, F-18, F-100, and F-117. Fighter aircraft hours ranged from 3.4 to 4594.5 with a mean of 990.41 (SD = 130.34). Other aircraft experience included AT-38, CT-39, OA-37, O-2A, OV-10, T-33, T-37, and T-38. All pilots had normal or corrected-to-normal vision and were unpaid for their participation.

Equipment

This experiment was conducted in the Fusion Interfaces for Tactical Environments (FITE) simulator at Wright-Patterson Air Force Base. FITE combined 6 projectors in a cubic projection room to provide a wrap-around view to both sides, above, and slightly below the cockpit. Displays provided included an out-the-window display, several liquid crystal head-down displays, a head-up display, a helmet-mounted display, and localized and non-localized auditory displays. The cockpit also included an F-16 throttle and stick for control. Figure 1 provides an illustration of the FITE simulator.

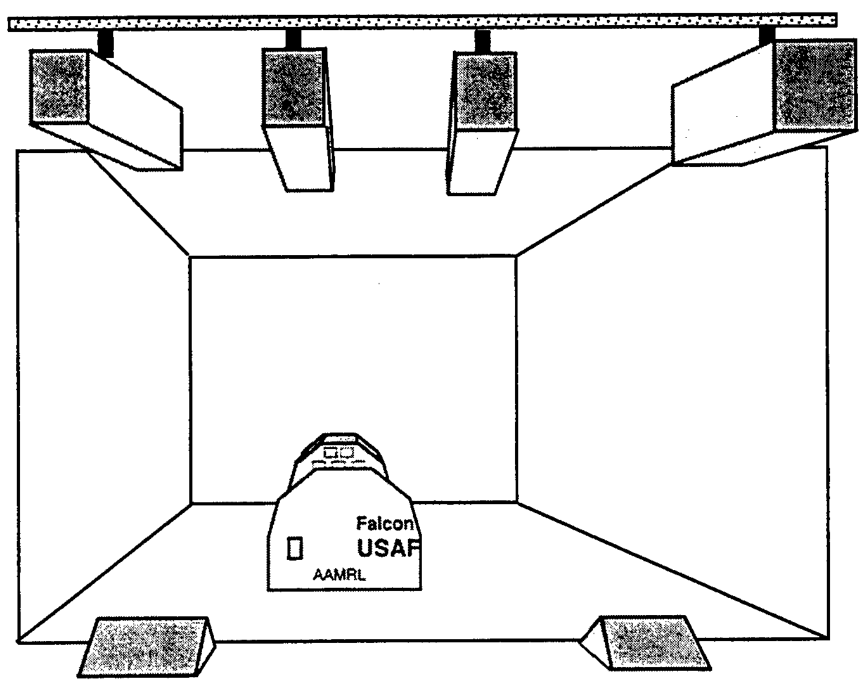

Figure 1. Schematic diagram of the layout of the Fusion Interfaces for Tactical Environments (FITE) simulator.

Conventional Cockpit

A "conventional" cockpit configuration consisted of traditional independent gauges and F-15 style displays of flight and tactical information. The liquid crystal displays provided were an Air-to-Air B-scope display, a Radar Warning Receiver display, an Airspeed Indicator, an Attitude Display Indicator, an Altimeter, and a dual-function display that consisted of a Systems Status Indicator and a Horizontal Situation Indicator. Figure 2 provides an illustration of the conventional cockpit.

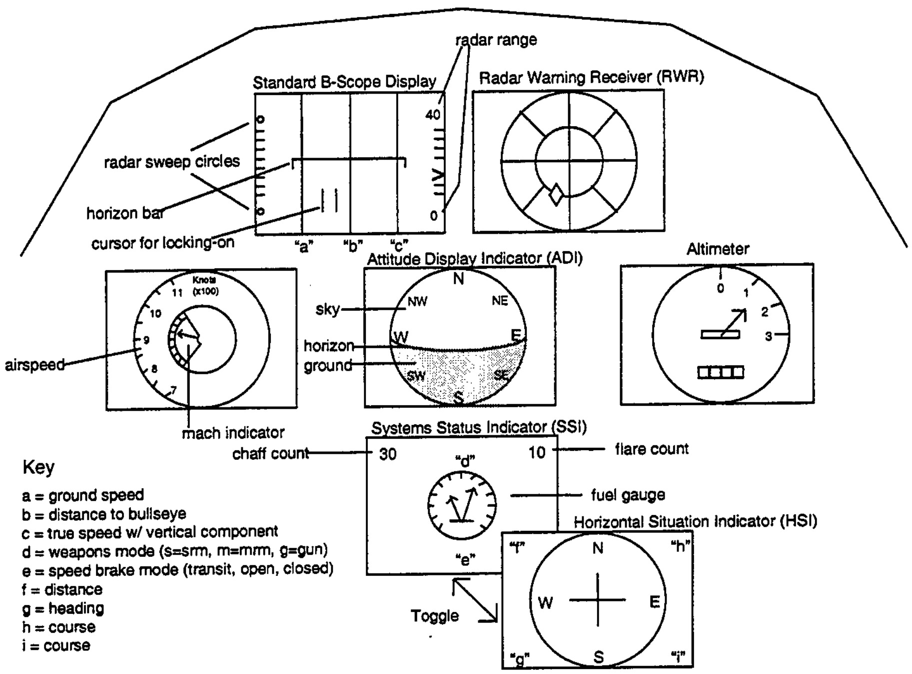

Figure 2. Schematic diagram of the conventional cockpit.

Candidate Cockpit

A virtually-augmented "candidate" cockpit configuration consisted of a variety of advanced, integrated interface concepts. A modified head-down display consisted of a pseudo large-screen display, generated by coupling the six in-cockpit liquid crystal displays. This screen provided a simulated out-the-window view including a horizon line, ground, sky, and moving ground textures augmented by monocular depth cues. A System Status Indicator and Ground Collision Avoidance System were also provided. Figure 3 provides an illustration of the candidate cockpit.

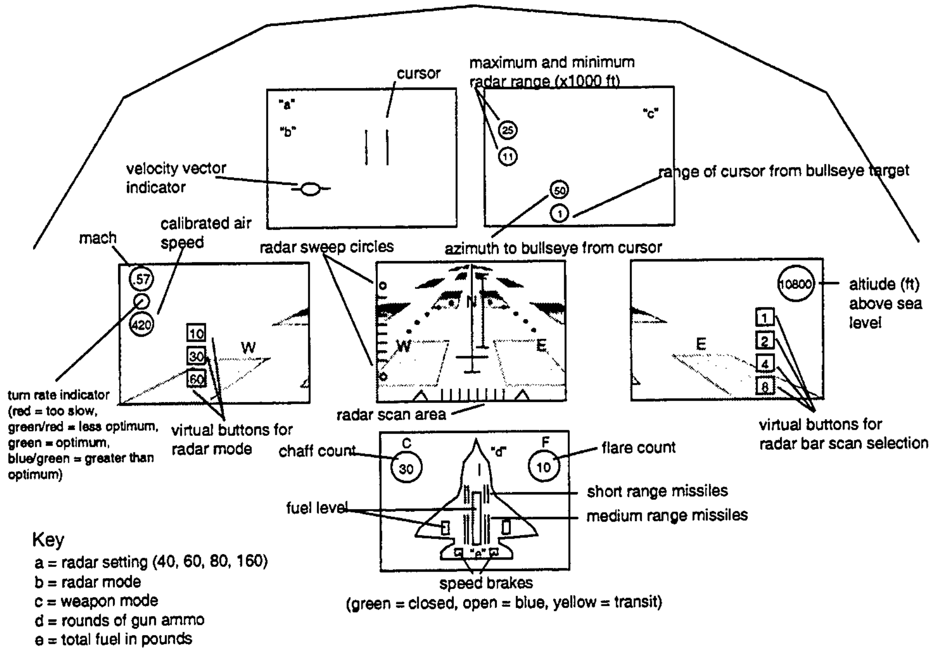

Figure 3. Schematic diagram of the candidate cockpit.

Scenario

The task was to fly an air defense mission. The mission began with the participant flying an oval-shaped Combat Air Patrol (CAP) pattern near his home airfield. The participant monitored a designated portion of airspace for the entrance of 4 bombers and 2 fighters. The participant's task was to locate and destroy the computer-controlled enemy bombers flying towards the home airfield and then to egress to safe airspace. Unless shot down, the bombers would attack the home airfield and then turn around to depart. The two human-controlled hostile fighters attempted to defend the enemy bombers by shooting down the participant. The simulation also included a computer-controlled friendly F-15 fighter and a computer-controlled Airbus airliner flying predetermined routes.

The complex ROE defined the flight scenario and weapons engagement procedures. Over 125 ROE defining specific procedures for aviating, navigating, and communicating were specific to each mission phase. The phases included the CAP, Intercept (attacking bombers), Defcon (dealing with the fighters), and Egress (returning to the home area). The mission was terminated if the participant was shot down, ran out of fuel, or successfully destroyed all bombers and returned to safe airspace.

Dependent Measures

Mental Workload

Mental workload was assessed using the Subjective Workload Dominance Technique (SWORD; Vidulich, Ward, & Schueren, 1991). The SWORD uses a series of bipolar relative judgments comparing the mental workload of different task conditions. There are three main steps to using the SWORD technique: 1) collecting the raw judgment data; 2) constructing the judgment matrix; and 3) calculating the SWORD ratings.

Collecting the Raw Judgment Data. Each pair of tasks appears on either side of a line on the evaluation form. Possible ratings are represented by 17 slots between the two tasks. Participants marked the middle slot if both tasks inflicted identical mental workload levels. Participants marked a slot closer to a certain task according to the amount of higher mental workload that task inflicted in comparison to the other task.

Constructing the Judgment Matrix. The experimental tasks are represented by the rows and columns of the judgment matrix. Each cell represents the comparison of the tasks in that row with the task in that column. Cells in which a task is compared with itself are filled with the value 1. Each cell in the upper-right triangular area of the matrix is filled with the participant's evaluation of the amount of higher mental workload inflicted b the row task over the column task. A value of 1 is entered if the participant marked the middle slot. Possible values are 2 to 9 for the marks closer to the left-side task. The reciprocal of the number is used for marks closer to the right-side task (possible values are 1/2 to 1/9). The lower-left triangular area of the matrix is filled in with the reciprocals of the corresponding upper-right cells.

Calculating the Ratings. An n x n matrix will produce n ratings, one rating for each task. The rating for each task is found by calculating the geometric mean for each row of the matrix. The task ratings are a decimal value between 0 and 1 and are normalized so that all ratings sum to 1. Higher ratings indicate higher levels of mental workload. In this experiment, each participant's SWORD evaluation provided mental workload scores for the eight task conditions defined by the two cockpits and the four mission phases.

Situation Awareness

Situation awareness was assessed inferentially by a performance-based metric called the Global Implicit Measure (GIM; Brickman, Hettinger, Roe, Stautberg, Vidulich, Haas, & Shaw, 1995). The GIM scores are based on a moment-to-moment comparison of the participant's actual performance versus the ideal performance as defined by the ROE. Certain responses are expected at each moment as defined by the ROE according to whether the participant is aware or not. If the participant's actual performance is the same as the ideal performance, then the score equals 1. If the actual performance is not the same as the ideal performance, then the score equals 0. Therefore, each ROE becomes an implicit probe of situation awareness.

Each implicit probe is scored at a rate equal to the frame rate of the simulation. A proportion score is calculated for each implicit probe by dividing the sum of 1's for a specified time period by the number of observations made during that time period. Proportion scores in each mission phase are combined to yield an overall mission phase GIM score. GIM scores were assessed for all four phases of flight in both cockpits.

Procedure

Each participant went through several training sessions prior to data collection. Training focused on reviewing simulator and ROE manuals as well as practice flying both the conventional and candidate cockpits. Each participant completed three sessions after training. Each session contained two blocks; one block contained three trials flying the conventional cockpit and the other block contained three trials flying the candidate cockpit. The order of the blocks within sessions was random across participants.

Mission outcome results, raw performance, and GIM scores were collected during each trial. Participants filled out the SWORD form following the completion of the simulation trials. A qualitative questionnaire was also filled out during the debriefing session.

RESULTS

Comparing ANOVA Results

Two cockpit by phase (2 x 4) within subjects ANOVAs were performed; one on the SWORD ratings and one on the GIM scores. The alpha level for significance was set at 0.05.

Mental Workload

Figure 4 presents average mental workload SWORD ratings by cockpit. There was a significant main effect of cockpit revealing that mental workload was higher in the conventional (0.1619) cockpit than in the candidate (0.0882), $F(1, 6) = 51.709$, $MSE = 0.0759$, $p < 0.001$.

Figure 5 presents average mental workload SWORD ratings by phase. A significant main effect of phase revealed that mental workload was highest in Defcon (0.2484), then Intercept (0.1519), then Egress (0.058), and lowest in CAP (0.0418), $F(3, 18) = 15.153$, $MSE = 0.1277$, $p < 0.001$.

The cockpit by phase interaction was also significant, $F(3, 18) = 23.803$, $MSE = 0.016$, $p < .001$. The difference between the cockpits was especially large in the Intercept and Defcon phases (0.1047 and 0.1716, respectively) in comparison with the CAP and Egress phases (0.0127 and 0.0466, respectively). In all cases the candidate cockpit had lower rated workload than the conventional cockpit.

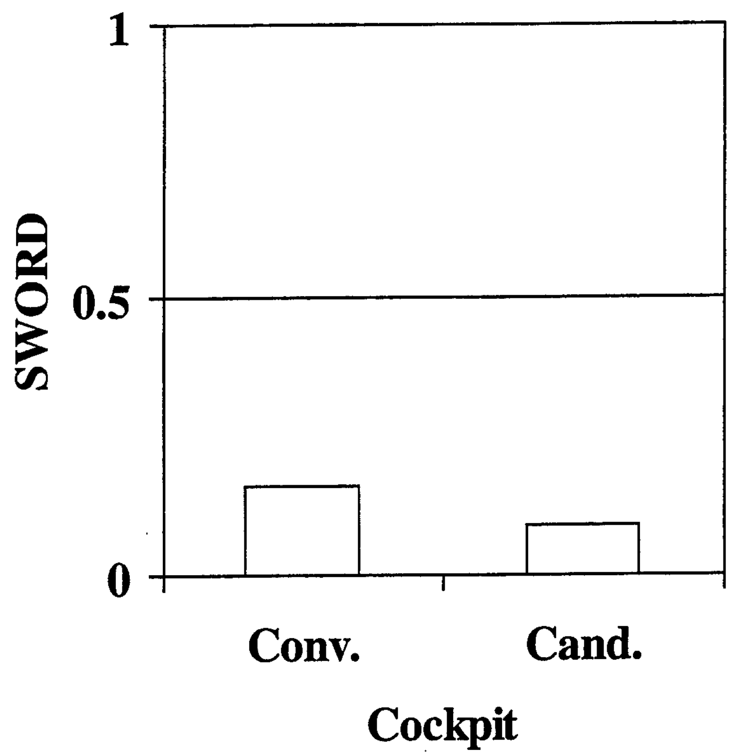

Figure 4. Average mental workload SWORD ratings by cockpit.

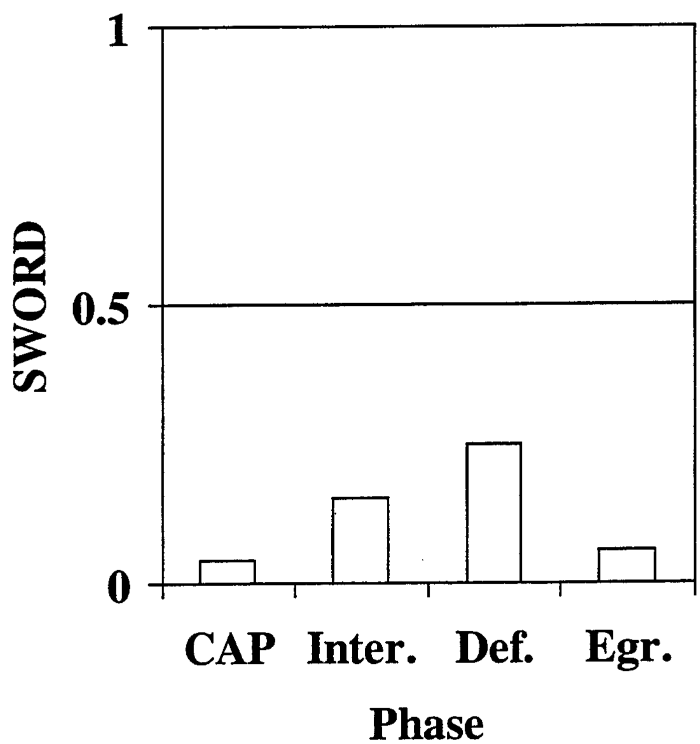

Figure 5. Average mental workload SWORD ratings by phase.

Situation Awareness

Figure 6 presents average situation awareness GIM scores by cockpit. There was a significant main effect of cockpit revealing that situation awareness was lower in the conventional (0.7927) cockpit than in the candidate (0.8232), $F(1, 6) = 9.017$, $MSE = 0.0131$, $p = 0.024$.

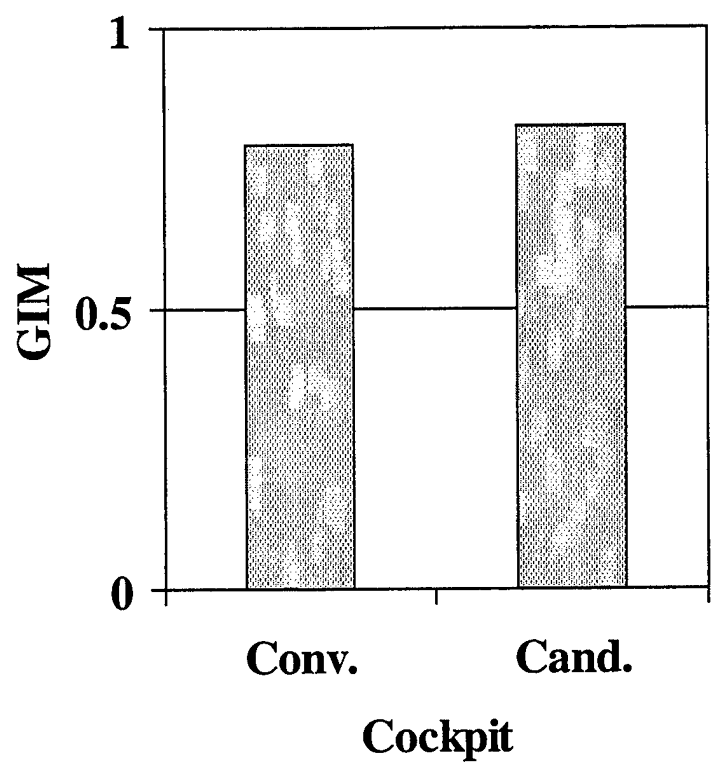

Figure 6. Average situation awareness GIM scores by cockpit.

Figure 7 presents average situation awareness GIM scores by phase. A significant main effect of phase revealed that situation awareness was lowest in Defcon (0.7161), then Egress (0.7741), then Intercept (0.8067), and highest in CAP (0.9349), $F(3, 18) = 46.237$, $MSE = 0.12$, $p < 0.001$.

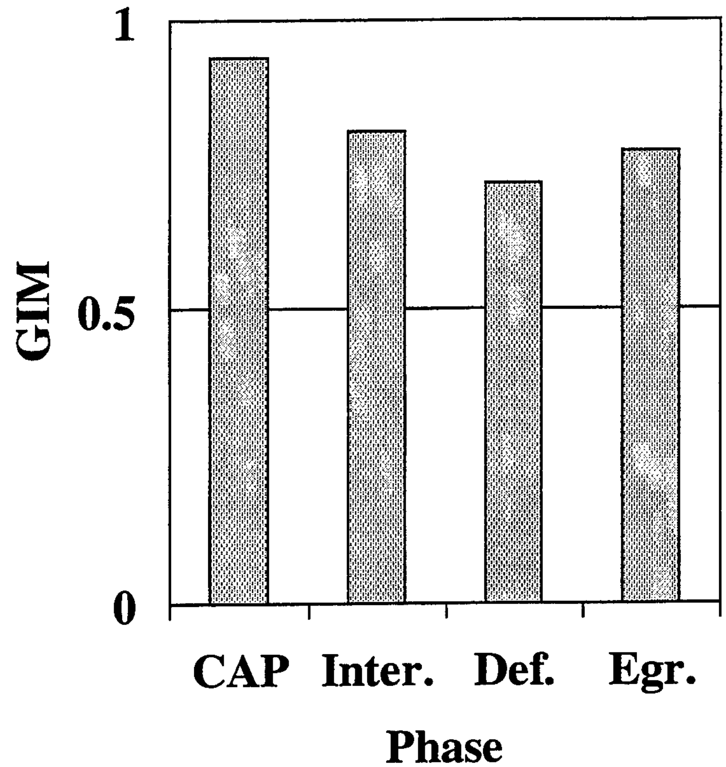

Figure 7. Average situation awareness GIM scores by

The cockpit by phase interaction was not significant in the GIM scores.

Correlation

A correlation between SWORD ratings and GIM scores was calculated for each participant across the eight task conditions defined by cockpit and mission phase. These correlations are presented in Table 1. Negative correlations found for all participants ranged from –0.1107 to -0.7872.

Table 1

Average SWORD/GIM correlation across subjects

Subject	Correlation
1	-0.5318
2	-0.7872
3	-0.6169
4	-0.7589
5	-0.6172
6	-0.7236
7	-0.1107

An average correlation across participants using Silver and Hollingsworth's (1989) algorithm was calculated and tested for significance. The Silver and Hollingsworth algorithm first converts each participant's correlation via a Fisher z transform prior to calculating the average and testing for significance. A significantly negative correlation was found, average $r = -0.6237$, $p < 0.0001$.

DISCUSSION

Unlike Endsley's (1993) result, a relationship between mental workload and situation awareness was detected. This was demonstrated in two ways. Contrasting Figure 4 with Figure 6, and Figure 5 with Figure 7 showed that manipulations that increased mental workload tended to lower situation awareness. Also, calculation of the correlation coefficient across the eight task conditions showed an inverse relationship.

There are several possible explanations as to why these results were different than Endsley's. First, Endsley's measurement of situation awareness used a very intrusive technique that stopped the simulation at random times to ask participants where the enemy aircraft was located. Furthermore, situation awareness, as previously defined, is more than just knowing (and remembering) the location of enemy aircraft. Second, the simulated air combat task used in that experiment did not appear to manipulate changes in mental workload or situation awareness. Only one mental workload measurement was assessed and compared to a situation awareness score that was not specific to any phase of the simulation. Therefore, it was not possible to determine how mental workload and situation awareness changed in relation to one another.

The demonstration that a relationship can exist between mental workload and situation awareness should encourage system designers to carefully consider the potential impact of any system change on both mental workload and situation awareness. Future experiments should employ different techniques for measuring both mental workload and situation awareness to determine if this relationship always exists. In some cases, as observed here, perhaps both mental workload and situation awareness can be improved. It is also possible in some cases that mental workload and situation awareness may trade off. Specifically, a trade-off might be expected to occur when new information is added to a display condition meant to increase situation awareness. If this information requires additional processing then mental workload should increase as well. This shows the importance of assessing both design drivers when assessing system effectiveness.

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APPENDIX A – SWORD ANOVA Table

SOURCE	SS	DF	MS	F	P
Cockpit	0.0759	1	0.0759	51.709	0.000
Cockpit *Subject	0.0088	6	0.0015		
Phase	0.3832	3	0.1277	15.153	0.000
Phase*Subject	0.1517	18	0.0084		
Cockpit*Phase	0.0480	3	0.0160	23.803	0.000
Cockpit*Phase*Subject	0.0121	18	0.0007		

APPENDIX B – GIM ANOVA Table

SOURCE	SS	DF	MS	F	P
Cockpit	0.0131	1	0.0131	9.017	0.024
Cockpit *Subject	0.0087	6	0.0014		
Phase	0.3600	3	0.1200	46.237	0.000
Phase*Subject	0.0467	18	0.0026		
Cockpit*Phase	0.0046	3	0.0015	1.809	0.182
Cockpit*Phase*Subject	0.0153	18	0.0008		

GLOSSARY

ANOVA	Analysis of Variance
CAP	Combat Air Patrol
Defcon	Defensive Condition
FITE	Fusion Interfaces for Tactical Environments
GIM	Global Implicit Measure
MSE	Mean Square Error
ROE	Rules of Engagement
SD	Standard Deviation
SWORD	Subjective Workload Dominance Technique